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A Multi-Criteria Logistics Analysis of Photovoltaic Modules for Remote Applications

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***Abstract*—Reliable electrical power grids are frequently unavailable or inaccessible in remote locations, including developing nation communities, humanitarian relief camps, isolated construction sites, and military contingency bases. This often requires sites to rely on costly generators and continuous fuel supply. Renewable energy systems (RES) in the form of photovoltaic (PV) arrays and energy storage present a rapidly improving alternative to power these remote locations. Previous RES literature and PV optimization models focused on economics, reliability, and environmental concerns, neglecting the importance of logistics factors in remote installations.**

This paper proposes additional optimization variables applicable to remote PV systems and compares PV module technologies. Logistics requirements such as system weight and volume are vital for shipment to remote applications. Furthermore, PV module efficiency and area power density are important factors because available land area can be limited in constrained sites. These factors should be considered, in addition to conventional economic and performance variables, to optimize an RES for remote locations.

The present study evaluates 29 PV modules utilizing manufacturer datasheets and supplier pricing. For each module, cost, efficiency, panel weight, and volume were collected to calculate the proposed logistics variables: area power density, weight power density, and volume power density. These variables were compared against module costs per watt, demonstrating cost-performance tradeoffs and enabling planners to select the best PV module for their application. Monocrystalline modules appear to provide the best balance of these factors, but developing technologies may challenge crystalline cells as they continue to mature. The best monocrystalline panels had efficiencies of approximately 20%, costs of $0.60/W, and power densities of 17 W/kg, 200 W/m^2, and 5,500 W/m^3. By comparing the logistics variables of PV modules as presented here, RES planners can develop more efficient designs better suited to the logistics of installing and operating at remote sites.

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Keywords—renewable energy systems, photovoltaics, PV, solar module, logistics, optimization, power density, remote, isolated sites

I. Introduction

At remote locations around the world where reliable access to power grids is unavailable, reliance on diesel generators is commonplace, with at least 10,000 MW installed worldwide [1]. Examples of these locations include developing nations, humanitarian relief camps, isolated construction sites, and military forward operating bases (FOBs). The challenges of operating on diesel generators include undesirable air and noise pollution, continual maintenance, and an ongoing fuel supply. This logistical requirement results in high transportation costs and presents a threat to energy resilience. Renewable energy, in the form of solar arrays with energy storage, presents a potential solution to the logistics issues that arise from traditional diesel fuel generation.

Decision-makers for renewable energy face the challenging task of selecting both the photovoltaic (PV) array and energy storage sizes to meet electrical load requirements at the lowest cost. Inherent tradeoffs between cost, performance, and other variables result in different system size solutions depending on the solution set desired [2]. Previous studies have analyzed renewable energy systems (RES) with various optimization methods and key variables selected. Several review articles demonstrate that the most common methods and goals of optimization are cost, reliability, and environmental impact [3]–[5]. However, system weight and volume are "highly critical" to remote PV applications [6].

Despite the significant contributions of the aforementioned research, there are little to no proven optimization methods that incorporate weight, volume, land area, and other logistics concerns vital to RES applications at

remote and isolated locales. Accordingly, the purpose of this paper is to examine the key variables required for the use of photovoltaics at remote locations, compare current and emerging PV module types using these variables, and determining the best candidates for remote and isolated applications.

II. Methodology: Defining Key Logistic Variables

The review defines and examines the key logistics variables of cost, efficiency, area, weight, and volume power densities for various selected PV module types, technologies, and manufacturers.

A. Cost

Cost is the nearly universal primary variable optimized in PV system design and selection. RES design engineers can consider cost based on the lowest initial capital cost, life-cycle cost, or levelized cost of energy [7], [8]. This paper defined cost as the portion of initial capital cost composed of the module purchase price, neglecting the balance-of-system (BOS) costs, including inverters, switches, and mounting hardware, which should be approximately the same for any panels used.

The National Renewable Energy Laboratory evaluates PV pricing based upon cost per power produced ($/W), which must be calculated from absolute costs given by solar pricing data ($/module) [9]. This dollars per watt method allows for comparison of power production across PV technology types that may possess very different efficiencies. For this analysis, 2019 US dollars were used.

B. Efficiency

The efficiency of the PV modules and technologies is measured in percent of power produced for a given solar insolation (efficiency = $P_{out}/P_{insolation}$) in percent of insolation recovered. Module efficiencies and power outputs used in this study were assumed to be obtained at Standard Test Conditions, which are AM1.5G sunlight at an irradiance of 1,000 W/m^2 and a temperature of 25°C [10]. Module efficiencies were used versus solar cell lab research efficiencies since this analysis is at a practical, system level.

C. Area Power Density

The area of PV panels required to produce a certain amount of power was determined by the area power density (W/m^2), which can be calculated from PV panel specifications. However, this quantity is proportional to PV module efficiency for a given insolation level or location. Therefore, this value will be estimated but will not need to be compared individually as the efficiency variable above already accounts for this factor.

D. PV Panel Weight (Power Weight Density)

Due to the logistics emphasis of this study, PV panel weight was an important variable to consider. Weight data is often provided by module manufacturers in terms of kg and were converted to W/kg to enable a comparison of overall power weight density. Weight density can be a significant factor in cases where transportation is very limited or expensive, such as aircraft cargo. In actual PV installations, there will be additional weight from the BOS equipment, such as mounting hardware and cables, but these weights are not considered in this study.

E. PV Panel Thickness and Volume (Power Volume Density)

PV panel volume is an essential logistics factor and distinct from weight since some methods of transport such as sea shipment depend on volume rather than weight. Shipping volumes for PV modules are directly dependent on the panel thickness; therefore, module thickness is an important attribute to consider. Using the panel thickness, size, and efficiency, an estimated power per PV unit volume was determined (W/m^3). Similar to weight, the volume contributed from BOS components is not considered in this study.

III. PV Technologies And Data Collection

As PV technology improves, more economical and high-efficiency options are becoming available for PV modules. This section will briefly describe each type of PV module and the potential advantages or concerns of each.

A. Monocrystalline Silicon (mono-Si)

Monocrystalline silicon continues to be one of the most widely produced solar technologies and is second in production today. It boasts high efficiencies but higher cost largely due to the need to create a nearly perfect, single-crystal structure in the Si wafers, which comprise as much of 40% of the manufacturing cost of the cell [11]. However, this structure creates a more efficient single-junction cell than many other types. Many of the PV modules studied in this review are mono-Si. According to the Fraunhofer ISE PV report, mono-Si makes up 32% of the global annual PV production [12].

B. Polycrystalline Silicon (poly-Si)

Polycrystalline is now the largest produced type of PV module worldwide, with over 60% of the market share according to Fraunhofer [12]. Polycrystalline, also called multi-crystalline, cells are formed in a similar process as mono-Si; however, there is no need to produce a single, pure crystal of silicon. Instead, the silicon is formed into rectangular ingots and allowed to cool naturally. This creates small, crystallized areas but not an entire single-crystal wafer. Cells produced with polycrystalline silicon material typically have lower efficiencies than mono-Si cells; however, poly-Si continues to improve and boasts a higher usable area for modules due to the square ingots vs. round mono-Si wafers which utilize cut corners. Peak mono-Si modules reach 24.4% while the best poly-Si currently only reach 19.9% efficiency, so the efficiency difference of mono-Si over poly-Si is around 4% [12].

C. Amorphous Silicon (a-Si) and HIT Cells

Amorphous silicon cells are formed with raw silicon that does not possess a long-range crystal structure like crystalline silicon. This means that a-Si has a much lower power conversion efficiency as compared to mono-Si or poly-Si. A-Si boasts a high absorption coefficient and can be formed into very thin films that can be flexible. This study looks at a hybrid of a-Si and crystalline silicon called HIT—Heterojunction with Intrinsic Thin-Layer modules. These

cells are formed with a layer of p-type a-Si and intrinsic a-Si added the top and bottom of a traditional n-type crystalline Si layer. Cell efficiencies of 25% have been reached with these types of cells by the Sanyo/Panasonic corporation [13]. Traditional a-Si thin-films were not considered due to their very low conversion efficiencies.

D. III-V Group Devices

III-V type solar cells are formed with elements of groups III and V on the periodic table and are recognized for their outstanding efficiency and extremely high cost. According to NREL estimates, commercial III-V cell prices range from \$100 to \$300/W, which largely confines the use of the cells to space applications [14]. One experimental GaAs thin-film prototype blanket was included in this study, but its cost is too large to consider for practical prime-power applications (\$100/W) [15].

E. Thin-films (CIGS)

CIGS are Copper Indium Gallium Selenide solar cells, one of the most popular choices for thin-film materials that can be deposited on flexible substrates. CIGS have a high absorption coefficient, making the material ideal for thin-film applications. The only traditional thin films included in this study are the CIGS solar thin-film blankets MiaSole Aurora Charger 97 and Brunton Solaris 62, which are both commercially available for a cost of \$606 and \$1500, respectively [15]. There are several other types of emerging solar cells, including other thin-films, Perovskites, and organic solar cells; however, they are excluded from the study because of their current experimental nature.

IV. Results and Discussion

This study evaluated 29 PV panel modules of several types: 18 monocrystalline, six polycrystalline, two a heterojunction design of crystalline and amorphous silicon (HIT cells), and three experimental thin-film solar blankets. The following criteria were required for each chosen module: cost, weight, module efficiency at standard test conditions, volume, and wattage. This data was collected from manufacturer datasheets and solar panel distributor pricing [15]–[20]. For the three thin-film blankets, some values were not given and had to be estimated.

Table 1 shows the selected logistics performance criteria for the 29 PV modules in this study. This table is sorted by lowest cost per unit power (\$/W). The weight, volume, and area power densities are given along with the module efficiency. The module types are listed where "Mono" is monocrystalline, "Poly" is polycrystalline, and the experiment III-V Group thin film device is listed as "III-V Matl." The best performer for each criterion is shown in bold. Note the exceptional power densities offered by the three thin-film blanket modules. Unfortunately, these come at a high cost from \$6/W up to \$100/W, making them currently impractical for large-scale prime power applications. If costs decrease, these devices would be ideal for remote, logistics constrained applications.

TABLE I. PV Module Logistics Performance Data

Manufacturer & Model	Cost (\$/W)	Module Effic. (%)	Power Density			Module Type
			Volume (W/m3)	*Weight (W/kg)*	*Area (W/m2)*	
Mission Solar MSE PERC 72	**0.57**	18.89	4723	17.36	188.9	Mono
Trinasolar TSM-DD05H.05(II)	**0.57**	18.7	5330	16.49	186.6	Mono
CanadianSolar CS6K-270	**0.57**	16.5	4713	14.84	165.0	Poly
Mission Solar MSE PERC 60	0.60	18.65	4662	17.03	186.5	Mono
Trinasolar TSM-DD05A .05(II)-305	0.60	18.6	5324	16.40	186.3	Mono
Peimar SG330P	0.61	17	4250	14.67	170.0	Poly
Peimar SG325P	0.62	16.74	4185	14.44	167.4	Poly
CanadianSolar CS3K-300MS	0.62	18.05	5159	15.63	180.5	Mono
Silfab SLG-M360Wp	0.63	19	4858	15.65	184.6	Mono
CanadianSolar CS3K-305MS	0.63	18.36	5245	15.89	183.6	Mono
Silfab SLA-M300Wp	0.64	18.4	4833	15.79	183.7	Mono
Qcells QCELLS295W	0.64	17.7	5520	15.69	176.6	Mono
Silfab SLA-M310Wp	0.67	19	4994	16.32	189.8	Mono
Peimar SG270P	0.68	16.6	4149	15.00	166.0	Poly
CanadianSolar CS1H-325	0.74	19.27	5506	16.93	192.7	Mono
Silfab SIL-330 BL	0.76	19.4	5108	16.92	194.1	Mono
CanadianSolar CS1H-330	0.77	19.57	5591	17.19	195.7	Mono
Grape Solar GS-STAR-100W	0.80	14.63	4181	12.20	146.3	Poly
Panasonic VBHN325SA17	0.98	19.4	4778	17.30	191.1	HIT
Panasonic VBHN330SA17	1.00	19.7	4928	17.84	197.1	HIT
Panasonic VBHN320KA01	1.02	19.1	5461	17.30	191.1	Mono
Solaria PowerXT-355R-PD	1.06	19.6	4906	16.90	196.2	Mono
Solaria PowerXT360R-PD	1.07	19.9	4975	17.14	**199.0**	Mono
Grape Solar GS_STAR-50W	1.30	12.5	3465	10.42	121.3	Poly
Solaria PowerXT-350R-AC	1.39	19.4	4837	15.91	193.5	Mono
Solaria PowerXT-355R-AC	1.44	19.6	4906	16.14	196.2	Mono
MiaSole Aurora Charger 97	6.25	16	7373	42.92	95.8	Thin Film
Brunton Solaris 62	24.19	12	**14413**	39.74	61.0	Thin Film
AltaDevices Prototype	100.00	**28.8**	14027	**150.00**	182.4	III-V Matl

The relationship of cost per watt versus module efficiency and power/area is shown in Figure 1. The relationship is largely horizontal, with most solar cell modules around $0.60 to $0.80 ($/W) with an efficiency of 18-20%. Highest efficiency available among similar-cost modules does increase with increased prices; however, a large increase in cost is needed for only a small increase in maximum efficiency. Power per unit area has the same trend as module efficiency, confirming that only one variable will need to be considered in PV module selection. A few data points show a slight variance, likely due to the border around each module that does not contain PV cells (despite being included in the panel area). Note that due to their high costs (greater than $6/W), the three thin blanket solar modules are not shown in the figures.

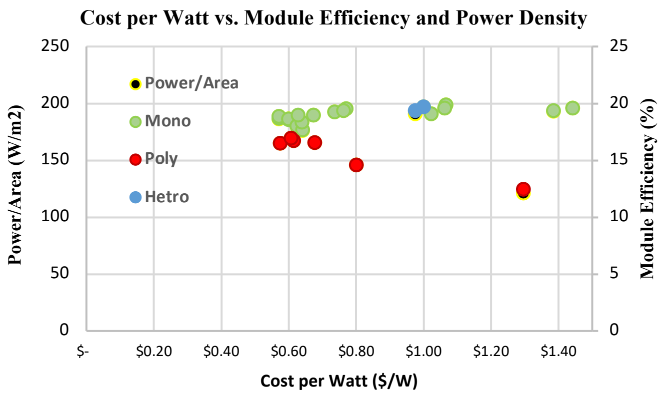

Fig. 1. PV module efficiency compared with power unit cost for three types of PV cells. Power per unit area is also graphed on the figure (black dots), but nearly all points coincide when mapped based on efficiency.

A comparison of weight density and cost per watt is shown in Figure 2. The majority of the solar panels weigh 15-20 kg each, resulting in weight power densities of 10-18 W/kg. The lighter modules are polycrystalline, but those modules were smaller in size. The typical size of most modules was 1,550-1,700mm (length) x 990-1,100mm (width) x 35-40mm (thickness).

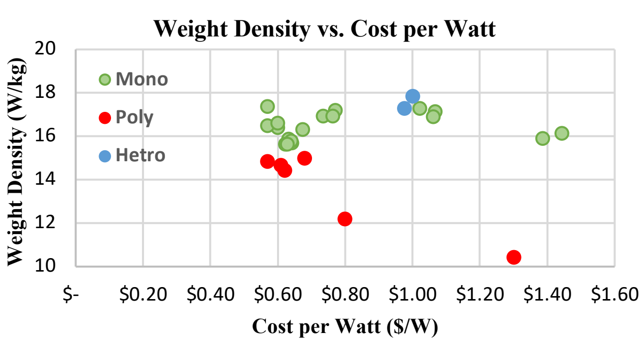

Fig. 2. PV module power weight density compared with cost. Notice the correlation between weight density and efficiency comparing Figures 1 and 2.

Figure 3 displays a comparison of cost per watt and volume power density, with typical values ranging from 4,000-5,800 W/m^3. Monocrystalline modules have a consistently higher volume density, likely due to their higher efficiencies. It is apparent that volume power density correlates with weight density for some but not all modules, so it may be necessary to consider both of these variables based on system requirements.

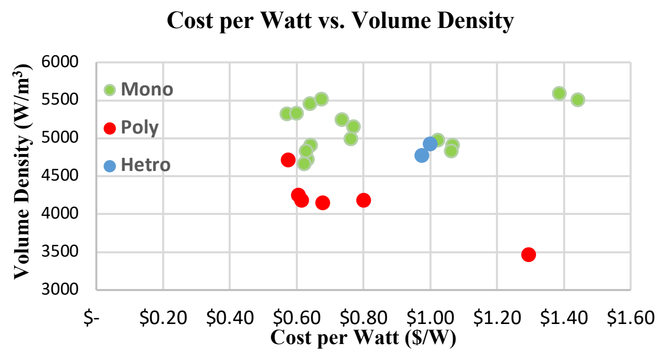

Fig. 3. PV module volume density compared with cost. Notice the similarities and differences between volume and weight densities comparison.

Figure 4 presents a 3D scatter plot of power volume density, weight density, and cost. From this graph, the ideal solar module in regard to these parameters can be visualized: the solar cell that has the lowest cost per watt, the highest power weight density, and the highest power volume density. Note area power density and efficiency are not shown on this graph but are still valid considerations.

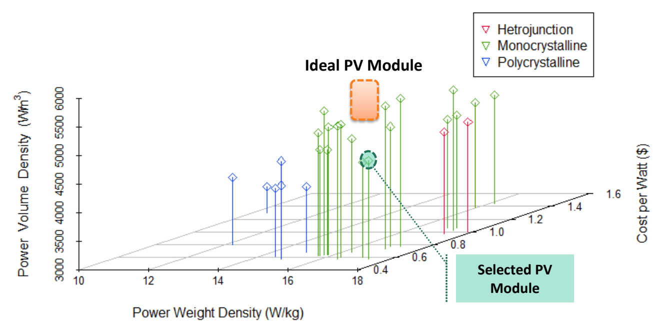

Fig. 4. 3D scatter plot of weight and volume density mapped against cost. Ideal modules with the lowest costs and highest power density are located in the top center front of the figure.

If weight density and cost are the primary considerations, the ideal solar cell in this figure is Mission Solar MSE PERC 72. Should different variables be selected as optimization factors, another module could be preferred.

V. Conclusion and Significance

For the purposes of remote applications, logistics concerns such as weight and volume are critical in addition to cost. This review utilized cost, efficiency, land area, weight, volume, and panel thickness as parameters for the selection of PV modules for remote installations. It was shown that low-cost monocrystalline modules are prime candidates for this application, though the actual selection of the model will depend on the relative importance of each variable. In future research, additional factors could be incorporated into the

analysis, such as installation costs, temperature dependence, and temporal degradation rates of the PV modules. Finally, thin-film blankets are a possible future technology that possess increased power volume density, weight density, and efficiency (for III-V types) over single-junction mono and polycrystalline solar cells, but are currently prohibitively expensive for large, prime power applications.

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